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PREDICTION OF COMPOSITE MATERIAL PROPERTIES USING TWO-DIMENSIONAL FINITE ELEMENT MICROMECHANICAL ANALYSIS

PANAGIOTIS BLANAS
COMPOSITES DEVELOPMENT BRANCH

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ABSTRACT

Two-dimensional finite element analysis is employed to predict the mechanical properties of unidirectional composite materials with isotropic constituents. The composite is treated as a transversely isotropic but homogeneous continuum, and linear elastic behavior is assumed for the analysis. Axisymmetric and plane strain finite element formulations along with the constitutive relations for transversely isotropic materials are used to obtain the apparent properties of the composite. The results are compared with results from micromechanics equations and experimental data.

CONTENTS

INTRODUCTION

The evaluation of the mechanical properties of fiber-reinforced composite materials has traditionally been a subject of significant practical importance. Many analytical and numerical studies have been performed on the prediction of composite mechanical properties.[1] In particular, approximate closed form expressions for composite elastic constants were given by Whitney and Riley[2] based upon a strain energy balance approach and classical elasticity theory, while bounds and expressions for the effective elastic moduli were given by Hashin and Rosen[3] based upon a variational method. Furthermore, a set of simplified micromechanics equations (SME) to predict the hydro, thermal, and mechanical properties of composites have been developed by Chamis[4] based upon a mechanics of materials approach. Numerical approaches include finite difference methods by Tsai, et al.[5] and Adams and Doner[6] which were used to predict composite elastic moduli values. Finite element analysis methods have also been utilized to describe the micromechanical behavior of composites. Adams and Crane[7] employed a generalized plane strain finite element formulation in conjunction with a laminated plate point stress analysis to predict the stress-strain response of composite laminates. Zhang and Evans[8] used an axisymmetric finite element approach and an energy equivalence principle to determine the mechanical properties of a composite with anisotropic constituents. In the present study, two-dimensional finite element analysis (FEA) methods are used to predict the mechanical properties of linear elastic composites with isotropic constituents. The assumptions and restrictions that have to be imposed under this type of analysis are presented and discussed. Numerical results are also presented and compared to those obtained from the SME by Chamis[4] and experimental results given by Adams.[9]

FORMULATION OF THE BOUNDARY VALUE PROBLEM

The composite system considered in the analysis is shown in Figure 1. It is assumed that the system can be represented by an infinite and periodic square array of unidirectionally oriented fibers with a relatively long axial dimension and of equal radius, *r*. The assumption of periodicity allows for the isolation of a repeating volume element cell outlined in Figure 1 and shown in Figure 2a for analysis. There are no displacements allowed across the boundaries of the repeating cell and displacements are restricted to those that cause the boundaries to displace parallel to the original boundaries. Also, due to symmetry about the y and z axes only one quadrant of the repeating cell, the unit cell in

1. CHAMIS, C. C., and SENDECKYJ, G. P. *Critique on Theories Predicting Thermoelastic Properties of Fibrous Composites.* J. of Composite Materials, v. 2, 1968, p. 332-358.
2. WHITNEY, J. M., and RILEY, M. B. *Elastic Properties of Fiber Reinforced Composite Materials.* AIAA Journal, v. 4, 1966, p. 1537-1542.
3. HASHIN, Z., and ROSEN, B. W. *The Elastic Moduli of Fiber-Reinforced Composite Materials.* J. of Applied Mechanics, v. 31, 1964, p. 223-232.
4. CHAMIS, C. C. *Simplified Composite Micromechanics Equations for Hygral, Thermal, and Mechanical Properties.* NASA Report TM-83320, National Aeronautics and Space Administration, Washington, DC, 1983.
5. TSAI, S. W., ADAMS, D. F., and DONER, D. R. *Effect of Constituent Material Properties on the Strength of Fiber-Reinforced Composite Materials.* AFML-TR-66-190, U.S. Air Force Materials Laboratory Technical Report, 1966.
6. ADAMS, D. F., and DONER, D. R. *Transverse Normal Loading of a Unidirectional Composite.* J. of Composite Materials, v. 1, 1967, p. 152-164.
7. ADAMS, D. F., and CRANE, D. A. *Finite Element Micromechanical Analysis of a Unidirectional Composite Including Longitudinal Shear Loading.* Computers and Structures, v. 18, 1984, p. 1153-1165.
8. ZHANG, W. C., and EVANS, K. E. *Numerical Prediction of the Mechanical Properties of Anisotropic Composite Materials.* Computers and Structures, v. 29, 1988, p. 413-422.
9. ADAMS, D. F. *Test Methods for Composite Materials.* Seminar Notes, U. S. Army Materials Technology Laboratory, 1988.

Figure 2b, need be considered in the analysis to describe the behavior of the repeating cell and, thus, completely characterize the state of stress and strain of the entire continuum. Two-dimensional finite element analysis is the method employed in this study to numerically solve the problem under consideration. Two separate finite element models, each employing two-dimensional plane elements, are created and used in the analysis. Under axial loading conditions axial symmetry is assumed for the composite and an axisymmetric problem is formulated in the 1-2 plane. When transverse loading of the composite is considered, plane strain conditions are assumed, and a plane strain model in the 2-3 plane is employed in the analysis. Typical axisymmetric and plane strain finite element models are shown in Figures 3a and 3b, respectively.

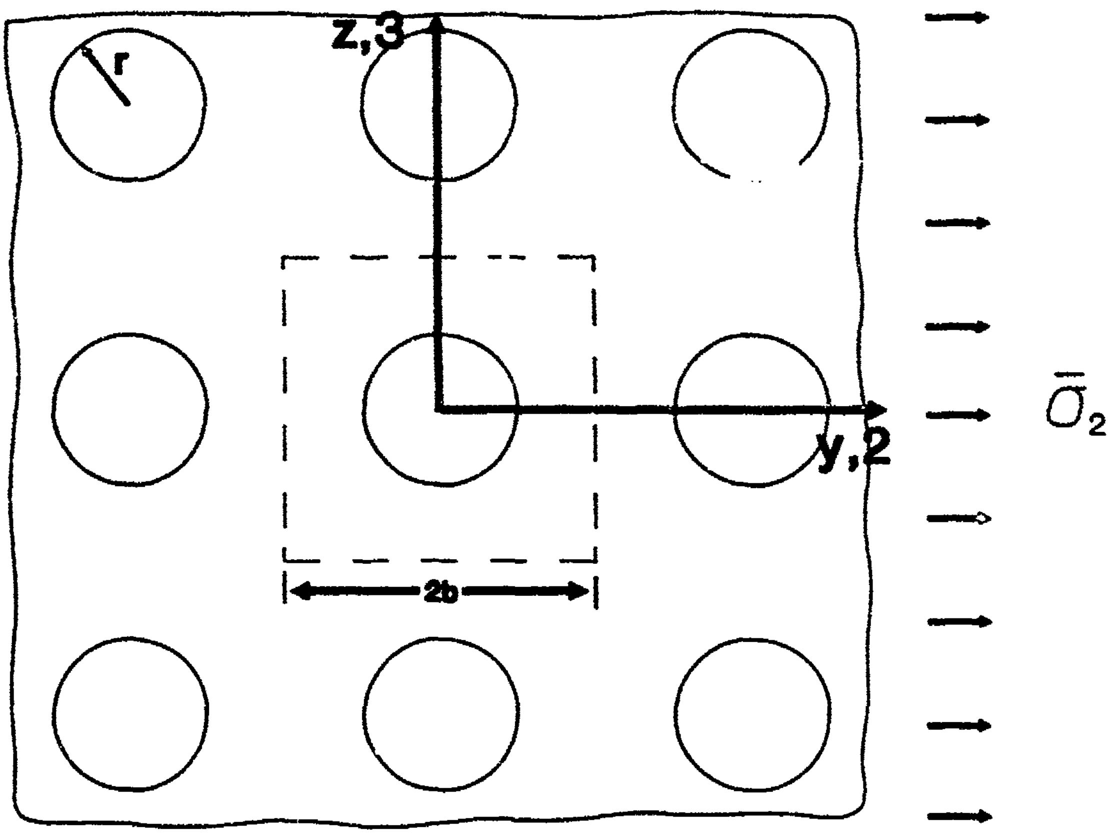


Figure 1. Square packing array unidirectional composite.

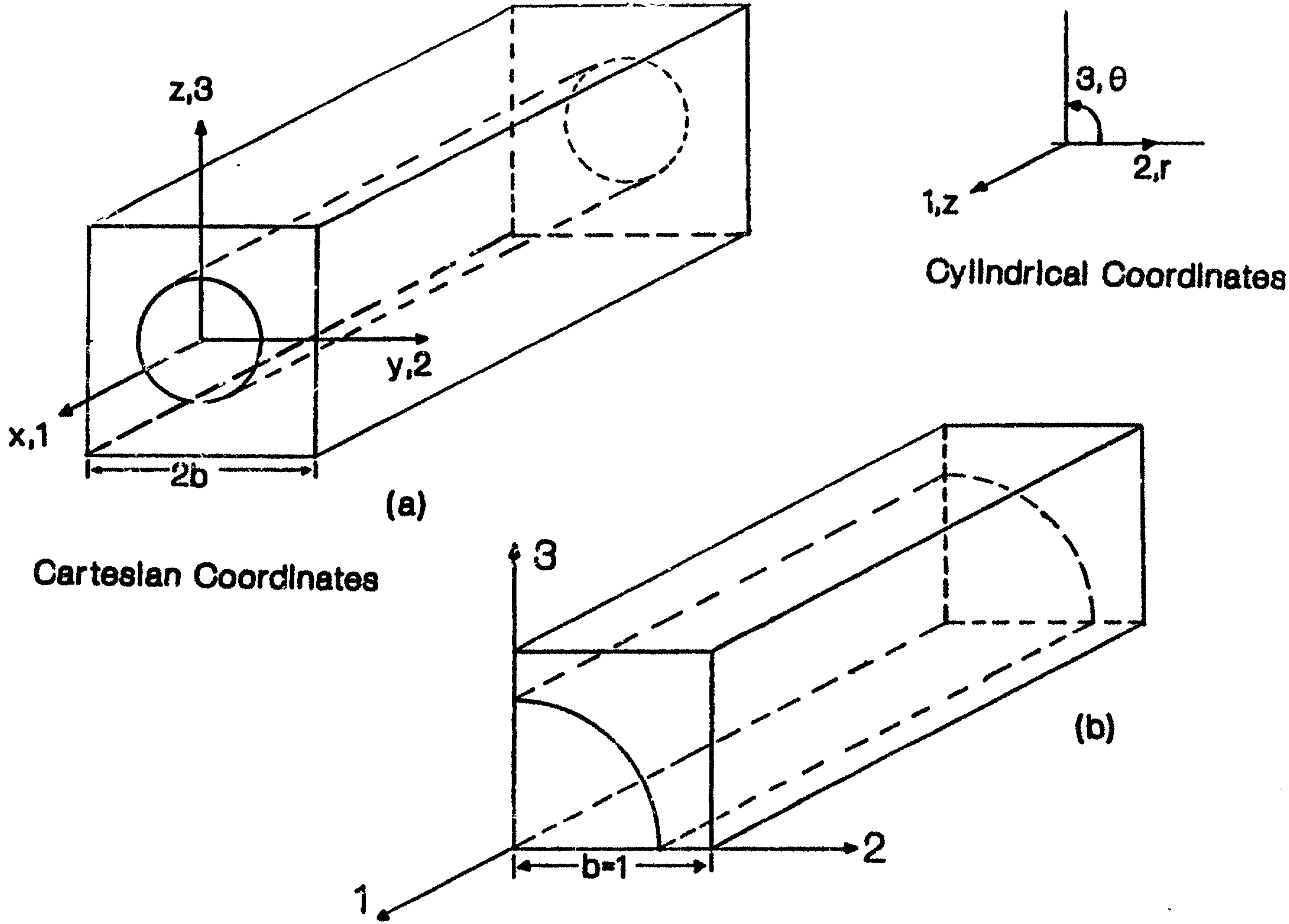


Figure 2. (a) Repeating volume element; (b) unit cell.

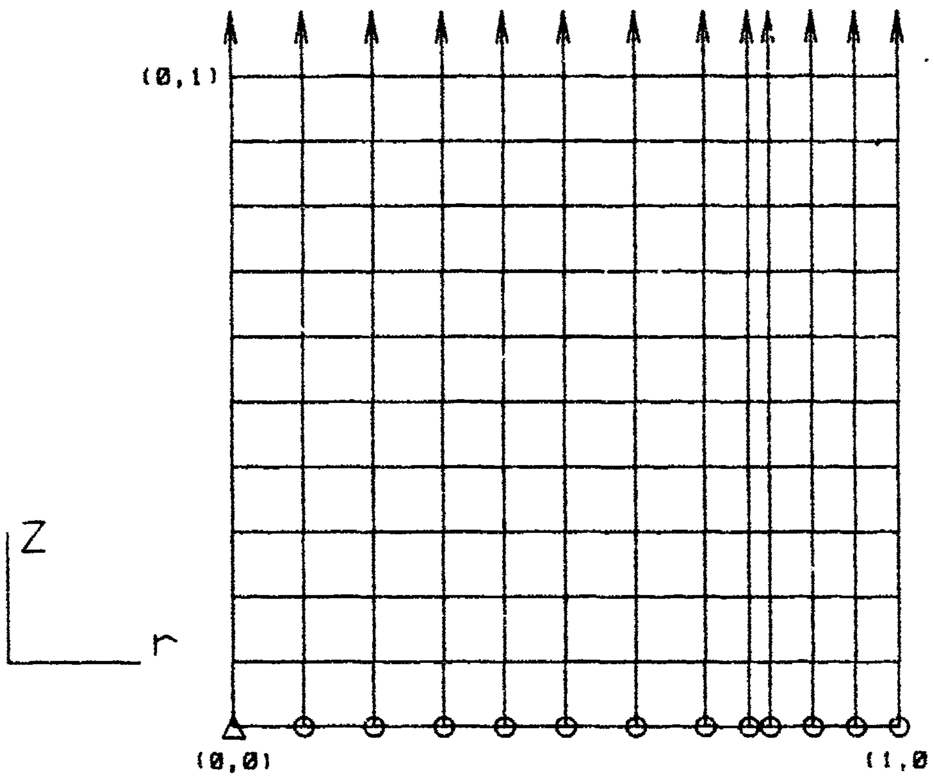


Figure 3a. Axisymmetric model.

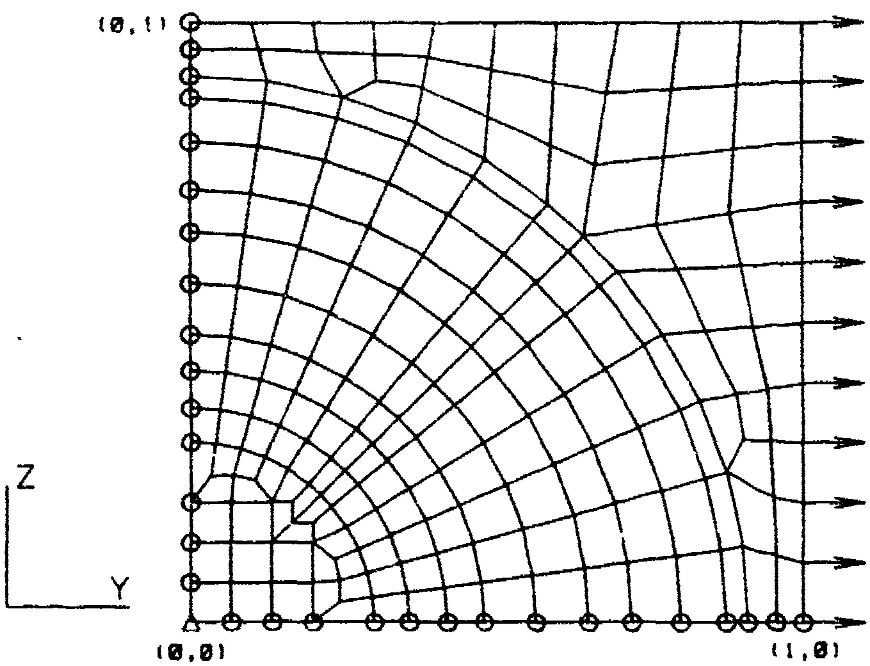


Figure 3b. Plane strain model.

Boundary Conditions and Loading

The appropriate boundary conditions along the external boundaries of the cell, as shown in Figures 3a and 3b respectively for each problem, can be expressed as follows:

Axisymmetric:

$$at \quad z=0, \; r\in[0,1]; \quad u_1=0 \tag{1}$$

$$at \quad r=0, \; z\in[0,1]; \quad u_2=0 \tag{2}$$

$$at \quad z=1, \; r\in[0,1]; \quad u_1=d_1 \tag{3}$$

$$at \quad r=1, \; z\in[0,1]; \quad u_2=-d_2 \tag{4}$$

Plane strain:

$$at \quad z=0, \; y\in[0,1]; \quad u_3=0 \tag{5}$$

$$at \quad y=0, \; z\in[0,1]; \quad u_2=0 \tag{6}$$

$$at \quad z=1, \; y\in[0,1]; \quad \frac{du_3}{dy}=0 \tag{7}$$

$$at \quad z=1, \; y\in[0,1]; \quad u_3=-D_3 \tag{8}$$

$$at \quad y=1, \; z\in[0,1]; \quad u_2=D_2 \tag{9}$$

$$\text{Plane strain condition;} \quad u_1=0 \tag{10}$$

where u_1, u_2, and u_3 are the displacement components in the 1, 2, and 3 directions, as defined in Figure 2, d_1 and D_2 are the magnitudes of the prescribed displacements and d_2 and D_3 are the magnitudes of the unknown displacements. Furthermore, continuity of tractions and displacements is assumed across the fiber matrix interface.

It is assumed that the composite is subjected to uniform normal loads applied at a distance from the volume element employed in the analysis; e.g., the remote stress field $\bar{\sigma}_2$ shown in Figure 1. When such loads are considered, a complex nonuniform state of stress is induced at the boundary of the unit cell due to dissimilar material properties of the fiber and matrix phases. However, because of symmetry, the boundaries of the unit cell must displace uniformly under uniform normal loads away from the cell boundaries. Therefore, specified uniform boundary displacements in the appropriate direction can be used to simulate the loading conditions for the problem. Such an approach applies the correct boundary conditions, makes the application of loads easier, and accounts for the nonuniform stress state at the boundary. For the present analysis both models are loaded using uniform prescribed boundary displacements, as shown in Figures 3a and 3b.

The relation between the traction components T_i at the external boundaries of the unit cell where prescribed displacements are applied and the farfield average stress components $\bar{\sigma}_i$ can be obtained from equilibrium considerations in the appropriate direction and can be express as:

$$\int_{s} T_i \, dS = S \, \overline{\sigma}_i \qquad (11)$$

where S is the cross-sectional area of the external boundary.

Assumptions of Analysis

In the present analysis an S2-glass/epoxy system is considered. The elastic constant values for each distinct phase of the composite are listed in Table 1.[9] Some of the modeling and analysis assumptions are as follows:

- Isotropic matrix and fiber
- Composite is transversely isotropic
- Linear elastic behavior
- Continuous reinforcement with perfectly circular fibers of equal radius
- No voids in either the fiber or the matrix
- Perfect fiber/matrix interface

Table 1. TYPICAL S2-GLASS FIBER AND EPOXY MATRIX PROPERTY VALUES

Property	S2-Glass	Epoxy
Tensile Modulus (MSI)	12.00	0.62
Poisson's Ratio	0.22	0.34
Shear Modulus (MSI)	5.00	0.23

In addition, effective stiffness properties of the composite are defined as an average measure of the stiffness of the material taking into account the properties of all phases of the heterogeneous media and their interactions. Based upon this definition, an averaging procedure is employed whereby the reaction forces, at the appropriate boundaries of the unit cell, along with Equation 11 are used to predict effective properties of the composite. The finite element analysis is used to determine the displacement fields and reaction forces for the composite.

Constitutive Equations

The square packing array composite with linearly elastic components employed in the analysis can be considered transversely isotropic.[10] The stress-strain relations for the composite and its components can be written as:

$$\sigma_i = C_{ij}\,\varepsilon_j \tag{12a}$$

$$\varepsilon_i = S_{ij}\,\sigma_j \tag{12b}$$

where σ_i are the stress components, ε_i are the strain components, and C_{ij} and S_{ij} are the stiffness and compliance matrices, respectively. For transverse isotropy where the 2-3 plane is the plane of isotropy the normal components of Equation 12b can be written as:

$$\begin{aligned}
\varepsilon_1 &= S_{11}\sigma_1 + S_{12}\sigma_2 + S_{12}\sigma_3 \\
\varepsilon_2 &= S_{12}\sigma_1 + S_{22}\sigma_2 + S_{23}\sigma_3 \\
\varepsilon_3 &= S_{12}\sigma_1 + S_{23}\sigma_2 + S_{22}\sigma_3
\end{aligned} \tag{13a}$$

where in terms of the elastic constants

$$S_{11} = \frac{1}{E_1}; \qquad S_{12} = -\frac{\nu_{12}}{E_1}; \qquad S_{23} = -\frac{\nu_{23}}{E_2}; \qquad S_{22} = \frac{1}{E_2}$$

and directions 1, 2, and 3 refer to the Cartesian coordinate system shown in Figure 2. When cylindrical coordinates are considered, Equation 13a can be written as:

$$\begin{aligned}
\varepsilon_z &= S_{11}\sigma_z + S_{12}\sigma_r + S_{12}\sigma_\theta \\
\varepsilon_r &= S_{12}\sigma_z + S_{22}\sigma_r + S_{23}\sigma_\theta \\
\varepsilon_\theta &= S_{12}\sigma_z + S_{23}\sigma_r + S_{22}\sigma_\theta
\end{aligned} \tag{13b}$$

where directions z, r, and θ refer to the cylindrical coordinate system shown again in Figure 2.

10. LEKHNITSKII, S. G. *Theory of Elasticity of an Anisotropic Elastic Body*. Holden-Day, San Francisco, CA, 1963.

The finite element analysis method is employed to solve the above formulated boundary value problem. Small displacements and linear elastic behavior are assumed throughout the solution. Two models each using two-dimensional solid elements were developed and used to carry out the analysis and obtain all required results. Details of these models and how they are used to extract the necessary information are outlined below.

Axisymmetric Model

The axisymmetric model is used to determine the behavior of the composite when loaded in the direction of the reinforcement. The assumption of axial symmetry has been shown to be valid when considering a unidirectional composite under axial loading;[11] and the filament packing array assumed when considering such a problem has little effect on the predicted property values.[8,12] Therefore, even though the axisymmetric formulation models a concentric cylindrical geometry of the matrix/fiber system as the repeating volume element, the predicted property values associated with axial loading of the composite should not be significantly affected by the axial symmetry assumption. Furthermore, the computational and modeling advantages of axial symmetry are considerable. To determine the displacement field and reaction forces for the composite under axial loading, a uniform normal displacement is applied at the $z = 1$ boundary in the axial, z, direction, as shown in Figure 3a. Note that at the radial boundary; i.e., at $r = 1$, the radial stress, σ_r, vanishes while the hoop stress, σ_θ, has a finite value. Substituting for the elastic constants and observing the conditions at the boundaries of the unit cell, the constitutive Equations of 13b reduce to

$$
\begin{aligned}
\varepsilon_1 &= \varepsilon_z = \frac{1}{E_1}\sigma_z - \frac{\nu_{12}}{E_1}\sigma_\theta \\
\varepsilon_2 &= \varepsilon_r = -\frac{\nu_{12}}{E_1}\sigma_z - \frac{\nu_{23}}{E_2}\sigma_\theta \qquad (14) \\
\varepsilon_3 &= \varepsilon_\theta = -\frac{\nu_{12}}{E_1}\sigma_z + \frac{1}{E_2}\sigma_\theta
\end{aligned}
$$

where ν_{12} refers to the major Poisson's ratio of the composite when loaded in the axial direction and is defined as

11. BLOOM, J. M., and WILSON, H. B., JR. *Axial Loading of a Unidirectional Composite*. J. of Composite Materials, v. 1, 1967, p. 268-277.
12. ADAMS, D. F., and TSAI, S. W. *The Influence of Random Filament Packing on the Transverse Stiffness of Unidirectional Composites*. J. of Composite Materials, v. 3, 1969, p. 368-381.

$$\nu_{12} = -\frac{\varepsilon_2}{\varepsilon_1} \tag{15}$$

Plane Strain Model

The plane strain model is used to determine the response of the composite under transverse normal loading. A uniform normal displacement is applied at the $y = 1$ boundary and in the transverse, 2, direction, as shown in Figure 3b. Consequently, a nonuniform displacement field is induced at the $z = 1$ free boundary of the unit cell, which contradicts boundary condition number 7 set in the Assumptions of Analysis Section. To eliminate this problem and verify boundary condition 7, which traditionally has been imposed when similar problems are solved,[5-7] a multicell approach is employed. The multicell approach utilizes multiple unit cells stacked in the z direction, while a uniform displacement load is still maintained at the $y = 1$ boundary, as shown in Figure 4. A convergence study is performed to determine the number of cells needed for the z boundary of the first cell in the stack; i.e., the cell boundary at $z = 1$, to displace uniformly and, thus, comply with boundary condition 7. Typical results of this study are shown in Figures 5 and 6. It is apparent from these plots that the solution converges rapidly and it takes only four cells for the boundary at $z = 1$ to displace uniformly. Note that for the multicell configuration and from equilibrium considerations in the z direction, the average stress component $\sigma_3(z) = 0$ since there is no applied load in that direction. Substituting for the elastic constants and observing the conditions at the boundaries of the bottom unit cell in the multicell stack, the constitutive Equations of 13a reduce to the following:

$$\begin{aligned}
\varepsilon_1 &= \frac{1}{E_1}\sigma_1 - \frac{\nu_{12}}{E_1}\sigma_2 = 0 \\
\varepsilon_2 &= -\frac{\nu_{12}}{E_1}\sigma_1 + \frac{1}{E_2}\sigma_2 \\
\varepsilon_3 &= -\frac{\nu_{12}}{E_1}\sigma_1 - \frac{\nu_{23}}{E_2}\sigma_2
\end{aligned} \tag{16}$$

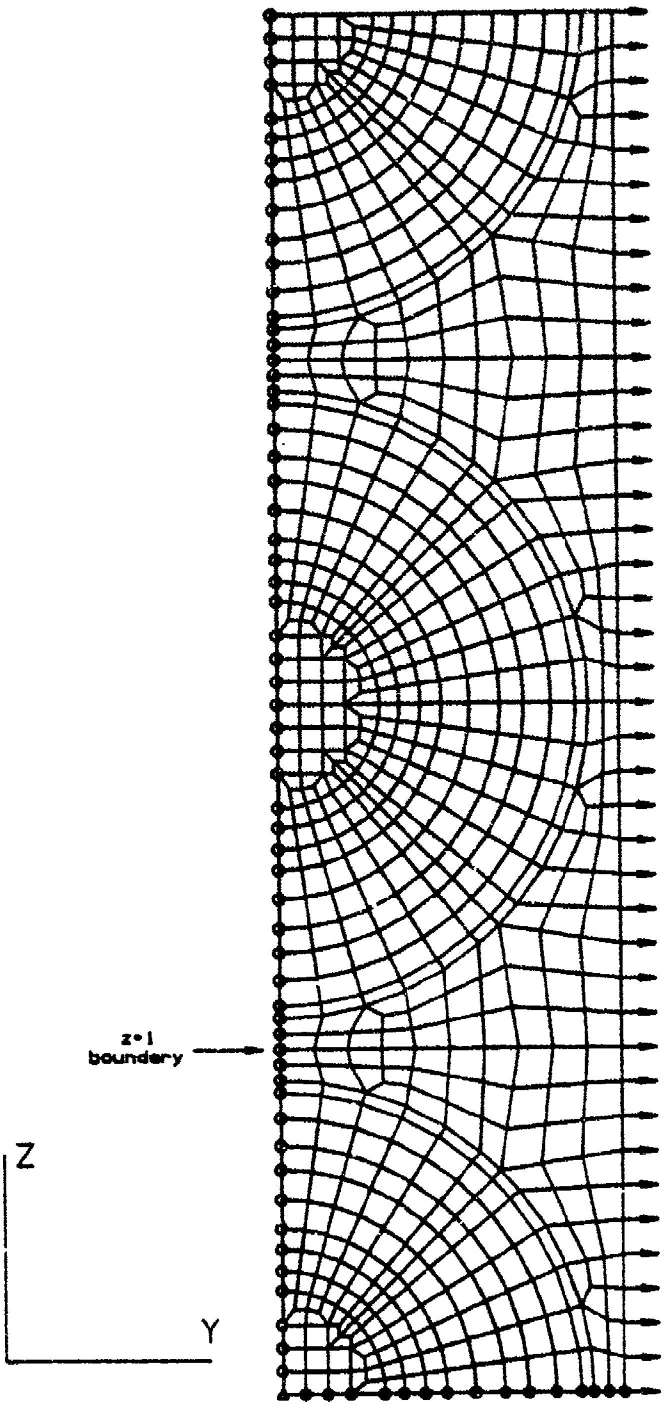


Figure 4. Multiple cell model.

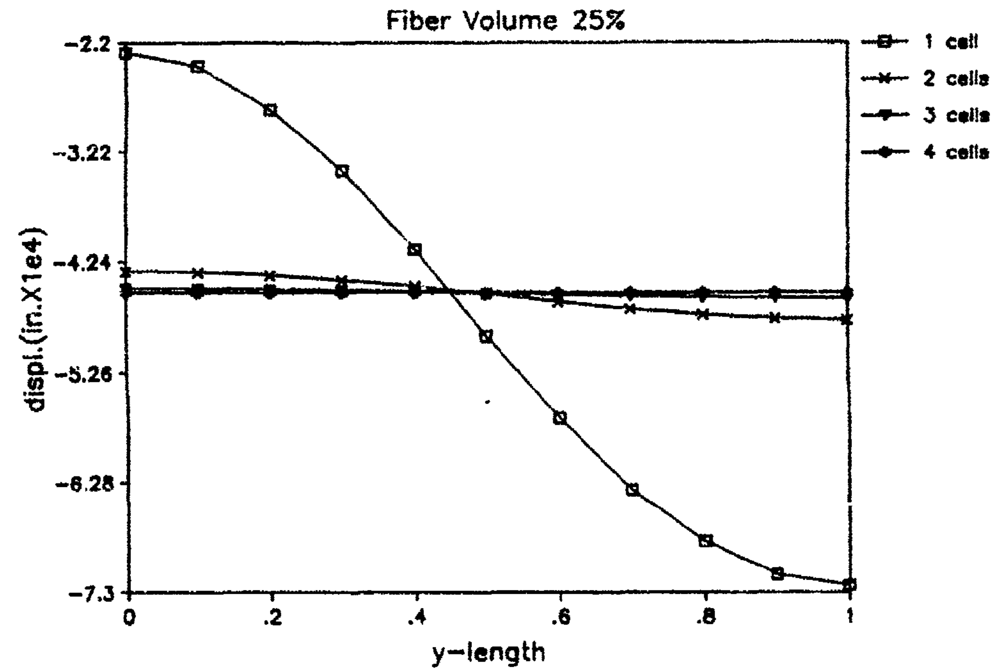


Figure 5. Displacement u3 at z = 1 boundary.

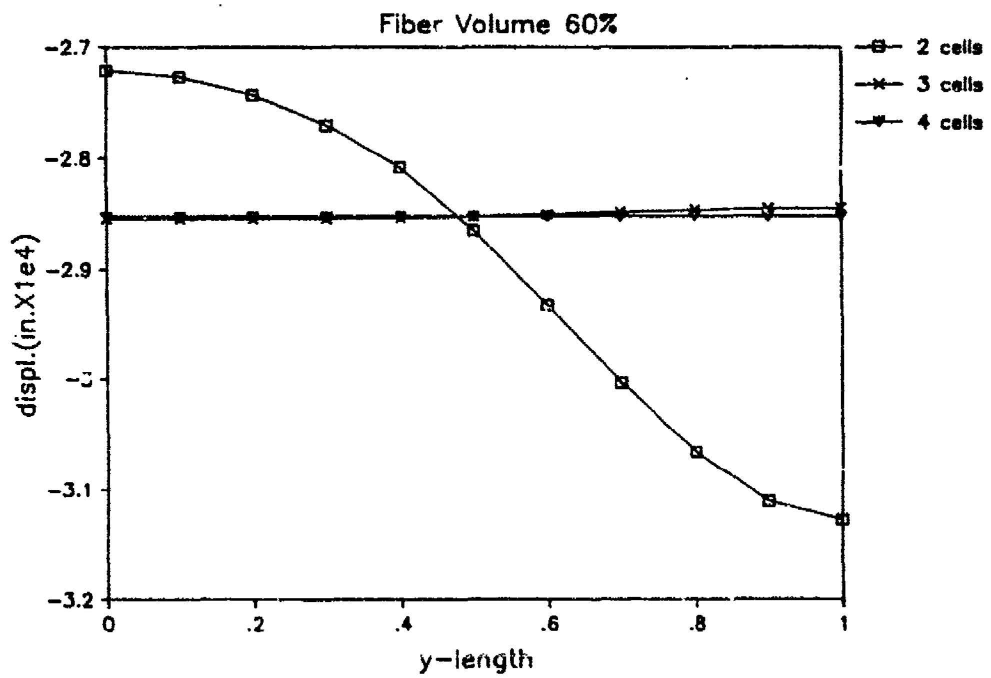


Figure 6. Displacement u3 at z = 1 boundary.

RESULTS OF THE ANALYSIS

The numerical results obtained from the finite element analysis provide a direct method for calculating the effective longitudinal and transverse properties of the S2-glass/epoxy composite system under consideration. The numerical procedures followed to obtain the effective properties are reviewed in the Axisymmetrical Case and Plane Strain Case Sections below. Numerical results obtained from this analysis are compared to results obtained from analytically developed micromechanical equations[4] and the experimental results of Reference 9. All pertinent results obtained and comparisons are shown in Table 2 and Figures 7 through 10.

Table 2. COMPOSITE MATERIAL PROPERTIES

Method	% Fiber Vol. (Nf)	E_{11} MSI	E_{22} MSI	ν_{12}	ν_{23}
MMA	0	0.62	0.620	0.340	0.348
FEA	0	0.62	0.615	0.340	0.337
MMA	10	1.76	0.88	0.328	0.344
FEA	10	1.76	0.77	0.325	0.426
MMA	25	3.46	1.18	0.310	0.340
FEA	25	3.46	1.04	0.304	0.412
MMA	50	6.31	1.88	0.280	0.330
FEA	50	6.33	1.92	0.272	0.306
MMA	60	7.45	2.34	0.268	0.325
FEA	60	7.44	2.55	0.261	0.255
EXP	60	7.50	1.75	0.280	—
MMA	65	8.02	2.63	0.262	0.322
FEA	65	8.01	3.03	0.255	0.230
MMA	100	12.0	12.0	0.22	0.200
FEA	100	12.0	11.9	0.22	0.218

NOTE: MMA = Mechanical of Materials Approach; FEA = Finite Element Analysis;
EXP = Experimental Data.

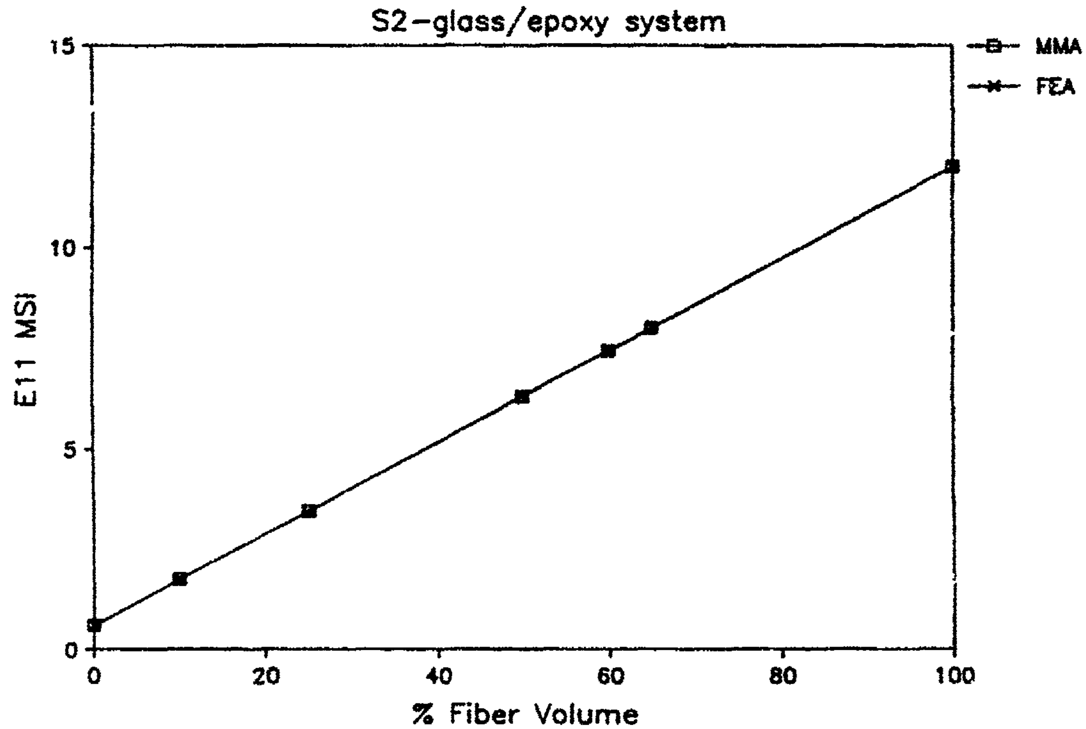


Figure 7. Composite effective properties.

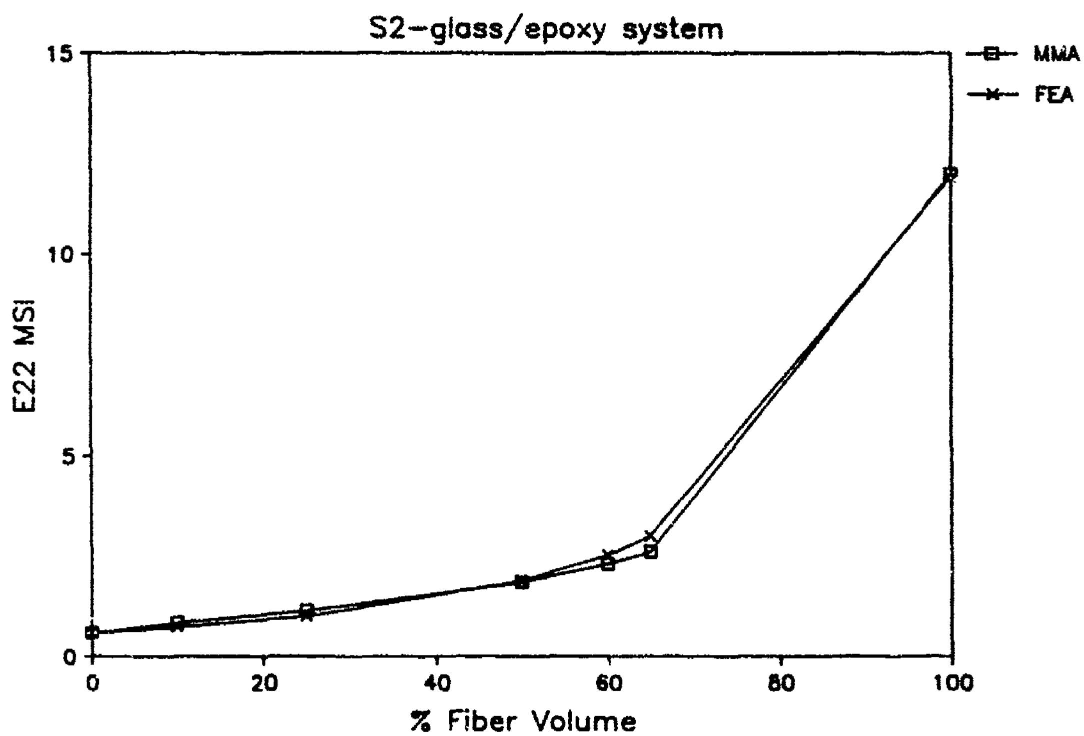


Figure 8. composite effective properties.

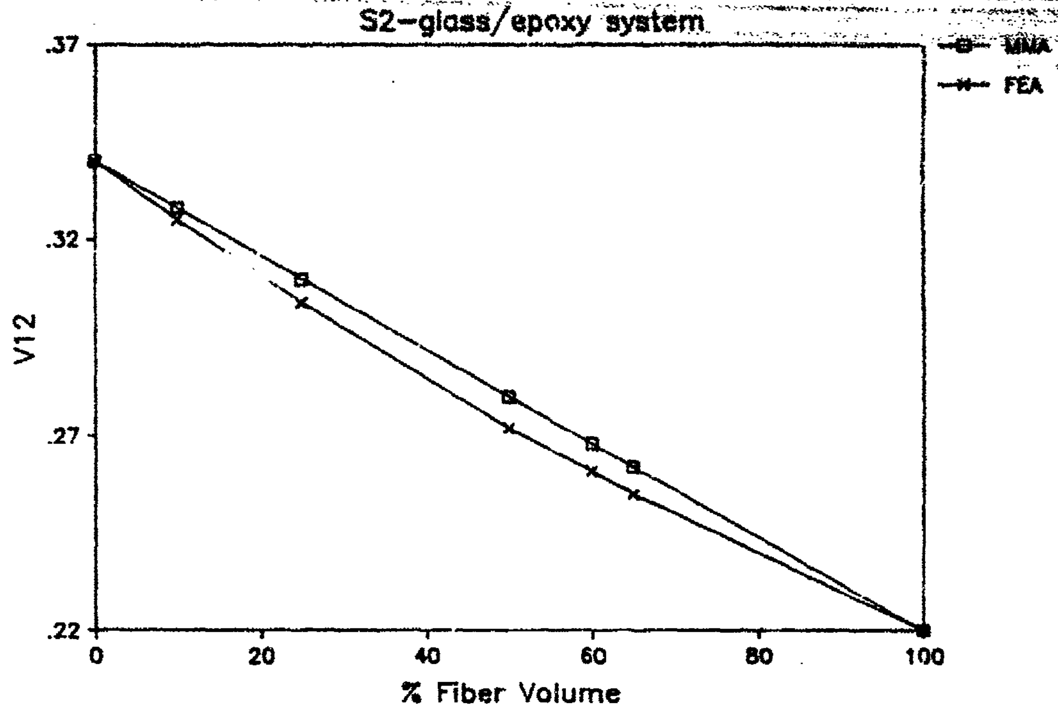


Figure 9. Composite effective properties.

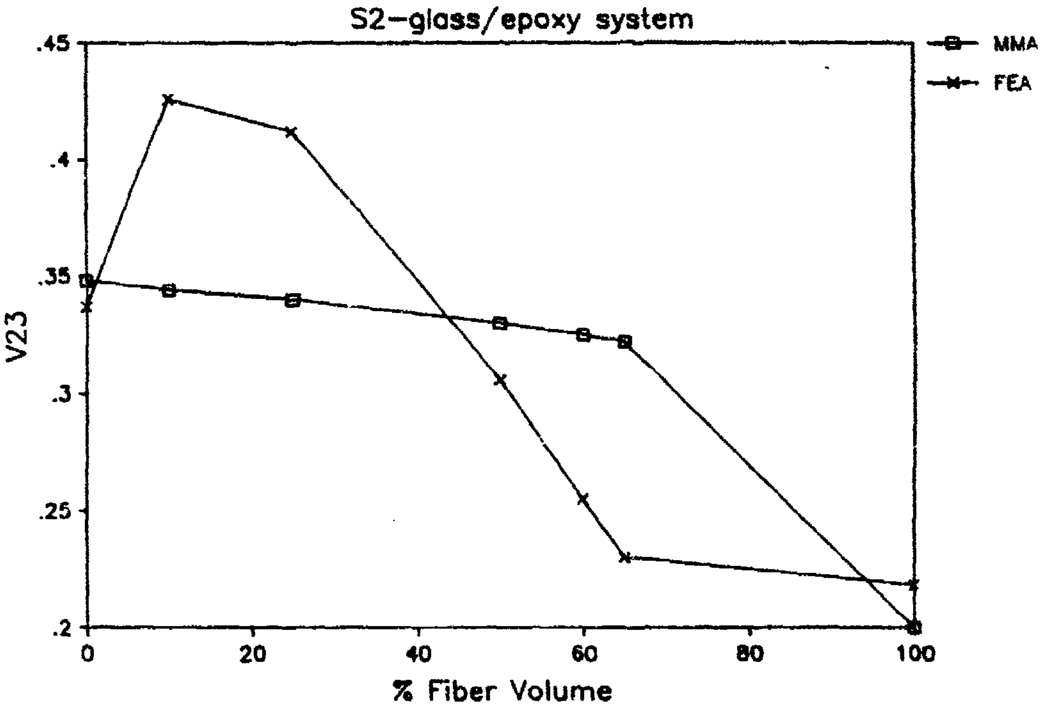


Figure 10. Composite effective properties.

Axisymmetric Case

Under the condition of axial loading the effective longitudinal modulus, $\bar{E}_1$, and Poisson's ratio, $\bar{\nu}_{12}$, of the composite are obtained in the following manner:

> A uniform displacement, d_1, is applied along the $z = 1$ boundary of the axisymmetric model and the solution of the finite element problem yields the unknown uniform displacement, d_2, along the $r = 1$ boundary. The average strains in the 1 and 2 directions can then be obtained from

$$\bar{\varepsilon}_1 = \bar{\varepsilon}_z = \left.\frac{d_1}{z}\right|_{z=1} \tag{17}$$

$$\bar{\varepsilon}_2 = \bar{\varepsilon}_r = -\left.\frac{d_2}{r}\right|_{r=1} \tag{18}$$

By employing Equation 11 the finite element solution also yields the average stress component $\bar{\sigma}_z$; the average hoop stress $\bar{\sigma}_\theta$ at the radial boundary is a result of the finite element solution as well. Using Equations 14 and 15 and substituting for the average quantities obtained from the finite element solution, the effective elastic constants $\bar{\nu}_{12}$ and $\bar{E}_1$ are given by

$$\bar{\nu}_{12} = \frac{\bar{\varepsilon}_2}{\bar{\varepsilon}_1} \tag{19}$$

$$\bar{E}_1 = \frac{1}{\bar{\varepsilon}_1}\left(\bar{\sigma}_z - \bar{\nu}_{12}\bar{\sigma}_\theta\right) \tag{20}$$

Plane Strain Case

Under the condition of transverse loading, the effective transverse modulus, $\bar{E}_2$ and Poisson's ratio, $\bar{\nu}_{23}$ are obtained in the following manner:

> A uniform displacement, D_2, is applied along the $y = 1$ boundary and the solution of the finite element problem yields the unknown uniform displacement, D_3, along the $z = 1$ boundary. It should be noted that only the first unit cell in the stack of the multicell problem is used to obtain numerical results for the plane strain case. The average strain in the 2 and 3 directions can then be obtained from

$$\bar{\varepsilon}_2 = \frac{D_2}{y}\bigg|_{y=b} \tag{21}$$

$$\bar{\varepsilon}_3 = -\frac{D_3}{z}\bigg|_{z=1} \tag{22}$$

By employing Equation 11 the finite element solution yields the average stress component $\bar{\sigma}_2$. Using Equation 16 and substituting for the average quantities obtained from the finite element solution, the effective elastic constants $\bar{E}_2$ and $\bar{\nu}_{23}$ are given by

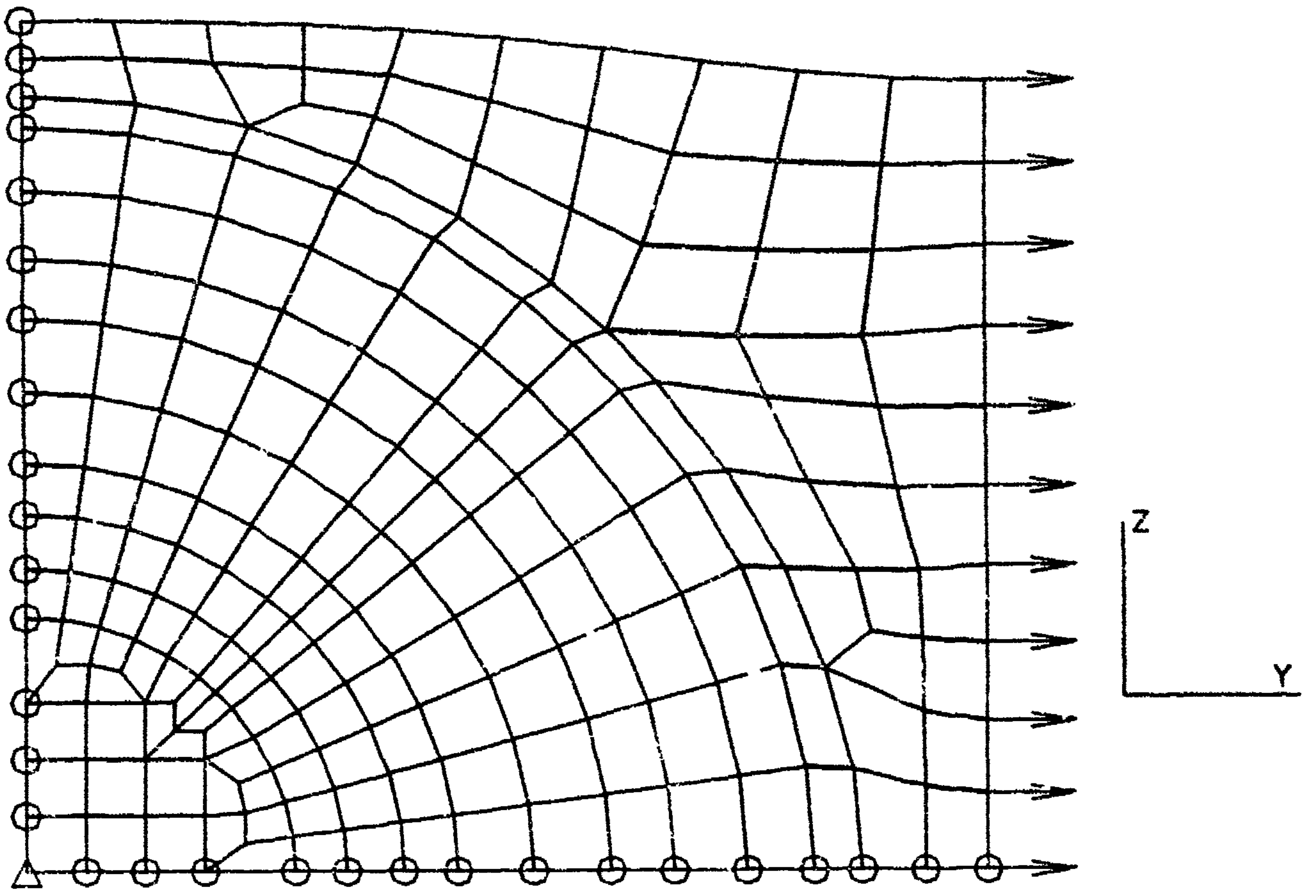
$$\bar{E}_2 = \left[\frac{\bar{\varepsilon}_2}{\bar{\sigma}_2} + \frac{(\bar{\nu}_{12})^2}{\bar{E}_1}\right]^{-1} \tag{23}$$

$$\bar{\nu}_{23} = \left[\bar{E}_2\left(\frac{\bar{\varepsilon}_2 - \bar{\varepsilon}_3}{\bar{\sigma}_2}\right) - 1\right] \tag{24}$$

CONCLUSIONS

In this study, the finite element method was used to predict the effective elastic properties of an S2-glass/epoxy transversely isotropic composite. Circular fibers in a square packing array and linear elastic behavior for the fiber and matrix phases was assumed in the formulation of the boundary value problem. Axisymmetric and plane strain finite element models of the problem under consideration were used simultaneously to obtain the elastic constants of the composite. Numerical results obtained from the finite element solution were compared with results obtained using classical micromechanics equations,[4] as well as with experimentally obtained results at 60% fiber volume.[9] It was found that values obtained for the longitudinal modulus $\bar{E}_1$, were in very good agreement with both theoretical and experimental results, while values for the rest of the elastic constants did not compare very well. Numerical values of the effective transverse modulus, $\bar{E}_2$, were found to be greater than both analytical and experimental values, particularly at higher fiber volumes. This can be attributed primarily to the assumptions made in the analysis and the two-dimensional formulation of the finite element problem. The plane strain assumption seems to result in a transversely stiffer composite system. It also produces erroneous results for the effective in-plane Poisson's ratio, $\bar{\nu}_{23}$. Furthermore, in utilizing two-dimensional finite element analysis two problems had to be solved to obtain all of the constants. However, the geometry employed in the two finite element problems is not the same. The axisymmetric problem solves the composite cylinder assemblage problem, which has been traditionally

employed to obtain approximate closed form solutions for the composite elastic constants, while the plane strain problem solves a single fiber system within a square boundary. This difference in geometric constraints at the boundaries might have affected the behavior of the composite system, thus introducing errors in the calculation of the elastic constants. The multicell plane strain problem successfully applied the correct condition at the cell boundary at $z = 1$. Figures 11 through 14 show how the model behaves and how the z boundary displaces as the number of unit cells increases from one to four.



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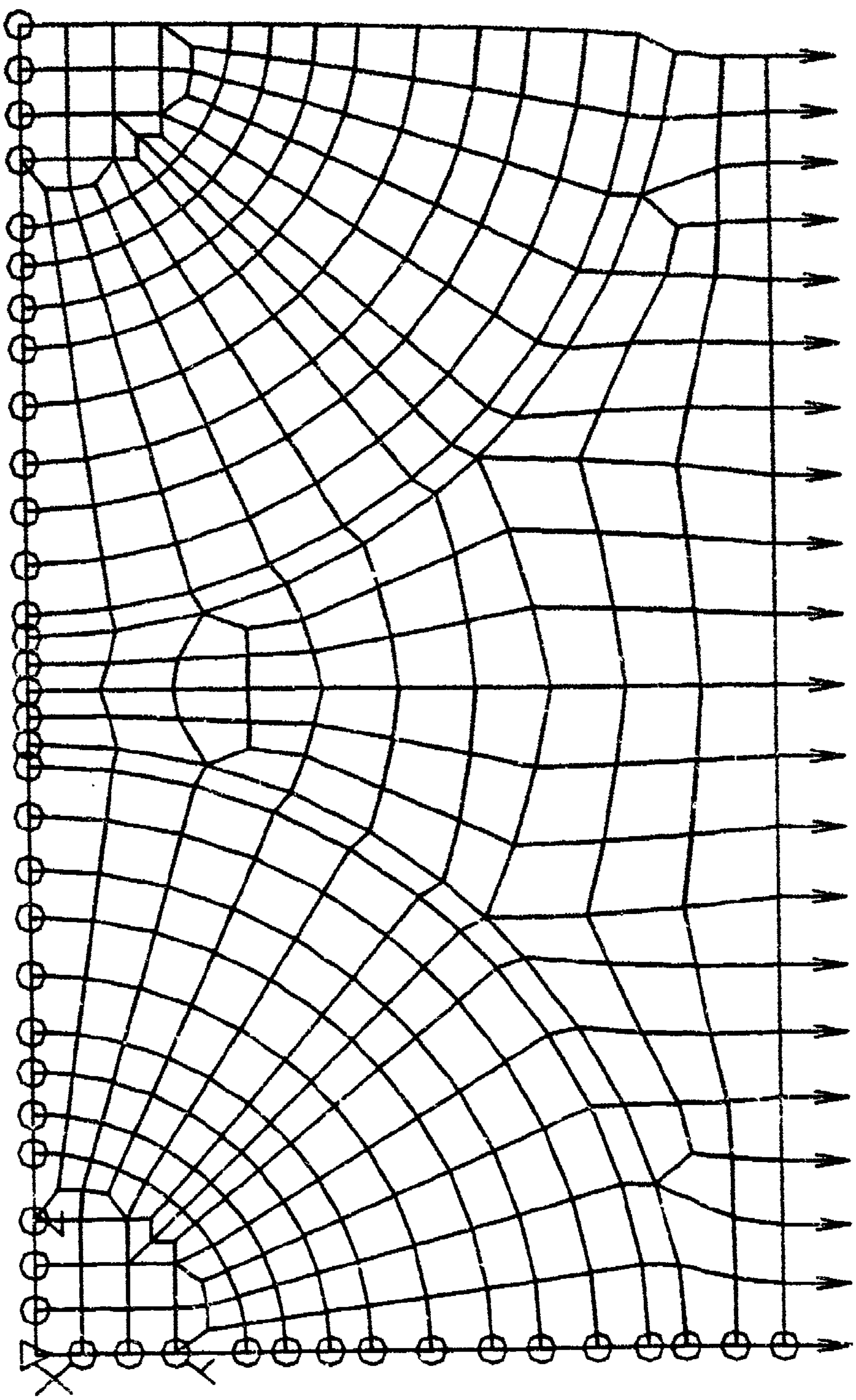

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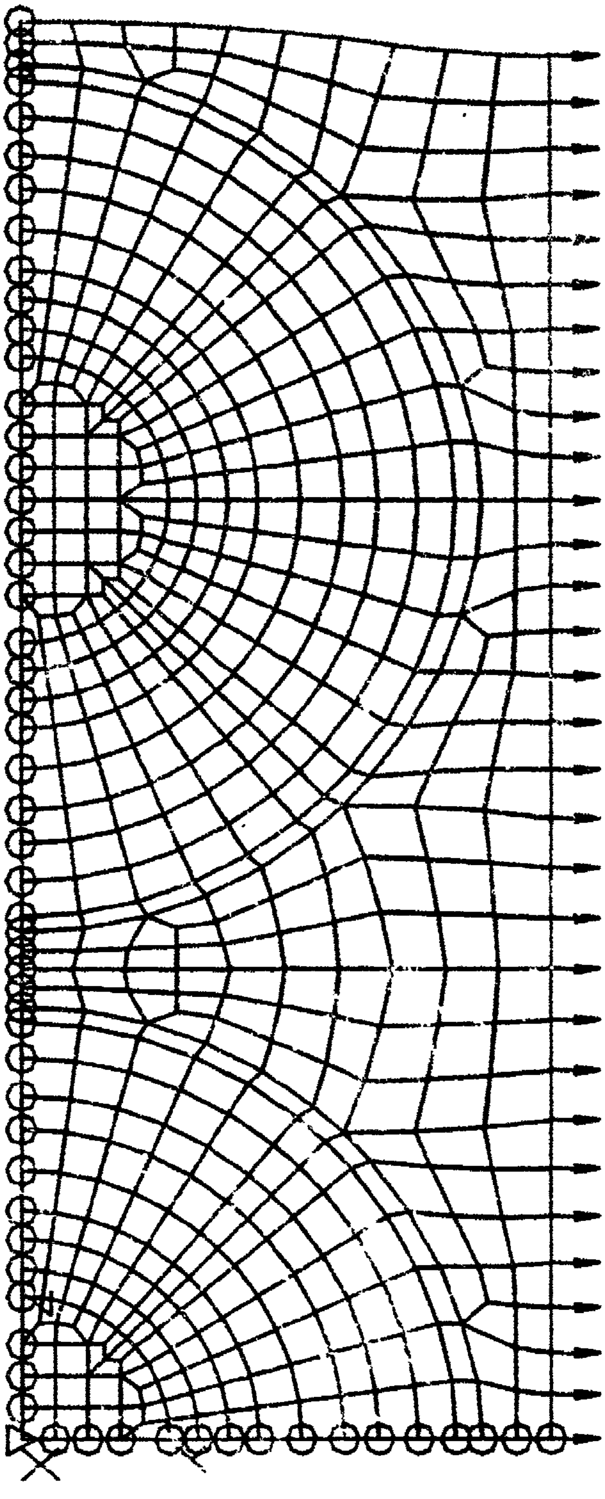

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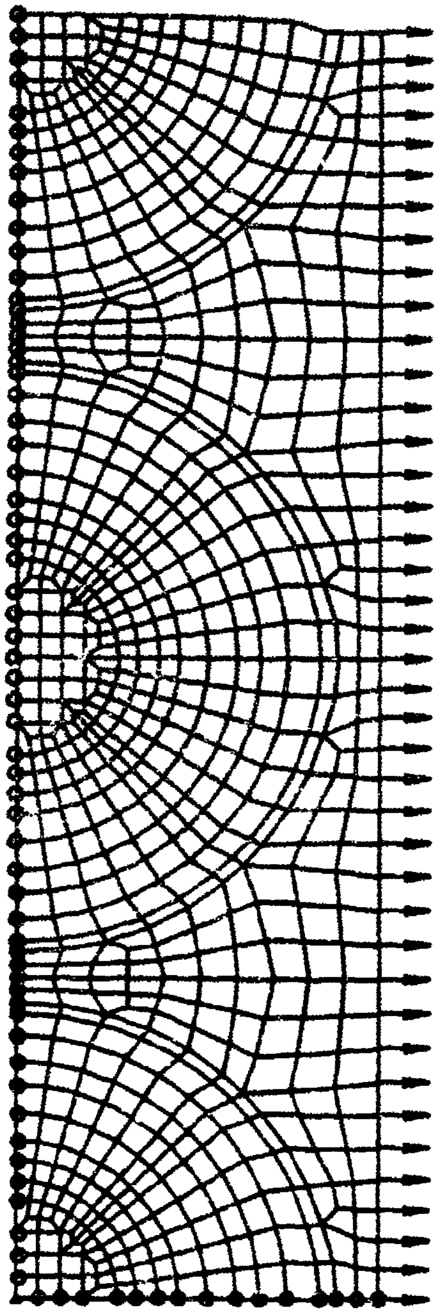

Figure 14.

In conclusion, it seems that the approach employed to model the micromechanical response of organic composite materials in this analysis is inadequate. A full three-dimensional finite element analysis study must be undertaken to relax some of the constraints and limitations imposed by the two-dimensional formulation. It should also be noted that assumptions made in the analysis, such as the fiber packing array and interface properties, must be reviewed and assessed.

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1	NASA - Lewis Research Center, 2100 Brookpark Road, Cleveland, OH 44135-3191
	Director, U.S. Army Materials Technology Laboratory, Watertown, MA 02172-0001
2	ATTN: SLCMT-TML
1	Author

U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
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